Copenhagen interpretation

The **Copenhagen interpretation** is an expression of the meaning of quantum mechanics that was largely devised in the years 1925 to 1927 by Niels Bohr and Werner Heisenberg. It remains one of the most commonly taught interpretations of quantum mechanics.[1]

According to the Copenhagen interpretation, physical systems generally do not have definite properties prior to being measured, and quantum mechanics can only predict the probabilities that measurements will produce certain results. The act of measurement affects the system, causing the set of probabilities to reduce to only one of the possible values immediately after the measurement. This feature is known as wavefunction collapse.

There have been many objections to the Copenhagen Interpretation over the years. Some have objected to the discontinuous jumps when there is an observation, the probabilistic element introduced upon observation, the subjectiveness of requiring an observer, the difficulty of defining a measuring device or to the necessity of invoking classical physics to describe the “laboratory” in which the results are measured.

Alternatives to the Copenhagen Interpretation include the many-worlds interpretation, the De Broglie-Bohm (pilot-wave) interpretation, and quantum decoherence theories.

1 Background

In the early work of Max Planck, Albert Einstein, and Niels Bohr, the occurrence of energy in discrete quantities was postulated in order to explain phenomena such as the spectrum of black-body radiation, the photoelectric effect, and the stability and spectrum of atoms. These phenomena had eluded explanation by classical physics and even appeared to be in contradiction with it. While elementary particles show predictable properties in many experiments, they become thoroughly unpredictable in others, such as attempts to identify individual particle trajectories through a simple physical apparatus.

Classical physics draws a distinction between particles and waves. It also relies on continuity, and on determinism, in natural phenomena. In the early twentieth century, newly discovered atomic and subatomic phenomena seemed to defy those conceptions. In 1925–1926, quantum mechanics was invented as a mathematical formalism that accurately describes the experiments, yet appears to reject those classical conceptions. Instead, it posits that probability, and discontinuity, are fundamental in the physical world. Classical physics also relies on causality. The standing of causality for quantum mechanics is disputed.

Quantum mechanics cannot easily be reconciled with everyday language and observation. Its interpretation has often seemed counter-intuitive to physicists, including its inventors.

The Copenhagen interpretation intends to indicate the proper ways of thinking and speaking about the physical meaning of the mathematical formulations of quantum mechanics and the corresponding experimental results. It offers due respect to discontinuity, probability, and a conception of wave–particle dualism. In some respects, it denies standing to causality.

2 Origin of the term

Werner Heisenberg had been an assistant to Niels Bohr at his institute in Copenhagen during part of the 1920s, when they helped originate quantum mechanical theory. In 1929, Heisenberg gave a series of invited lectures at the University of Chicago explaining the new field of quantum mechanics. The lectures then served as the basis for his textbook, *The Physical Principles of the Quantum Theory*, published in 1930.[2] In the book’s preface, Heisenberg wrote:

> On the whole the book contains nothing that is not to be found in previous publications, particularly in the investigations of Bohr. The purpose of the book seems to me to be fulfilled if it contributes somewhat to the diffusion of that 'Kopenhagener Geist der Quantentheorie' [i.e., Copenhagen spirit of quantum theory] if I may so express myself, which has directed the entire development of modern atomic physics.

The term 'Copenhagen interpretation' suggests something more than just a spirit, such as some definite set of rules for interpreting the mathematical formalism of quantum mechanics, presumably dating back to the 1920s. However, no such text exists, apart from some informal popular lectures by Bohr and Heisenberg, which contradict each other on several important issues. It appears that the particular term, with its more definite sense, was coined by Heisenberg in the 1950s,[3] while criticizing alternate “interpretations” (e.g., David Bohm's[4]) that had been developed.[5] Lectures with the titles 'The Copenhagen

Interpretation of Quantum Theory' and 'Criticisms and Counterproposals to the Copenhagen Interpretation', that Heisenberg delivered in 1955, are reprinted in the collection *Physics and Philosophy*.[6] Before the book was released for sale, Heisenberg privately expressed regret for having used the term, due to its suggestion of the existence of other interpretations, that he considered to be "nonsense".[7]

3 Current status of the term

According to an opponent of the Copenhagen interpretation, John G. Cramer, "Despite an extensive literature which refers to, discusses, and criticizes the Copenhagen interpretation of quantum mechanics, nowhere does there seem to be any concise statement which defines the full Copenhagen interpretation."[8]

4 Principles

Because it consists of the views developed by a number of scientists and philosophers during the second quarter of the 20th Century, there is no uniquely definitive statement of the Copenhagen interpretation.[9] Moreover, by different commentators and researchers, various ideas have been associated with it; Asher Peres remarked that very different, sometimes opposite, views are presented as "the Copenhagen interpretation" by different authors.[10] Nonetheless, there are several basic principles that are generally accepted as being part of the interpretation:

1. A wave function Ψ represents the state of the system. It encapsulates everything that can be known about that system before an observation; there are no additional "hidden parameters".[11] The wavefunction evolves smoothly in time while isolated from other systems.

2. The properties of the system are subject to a principle of incompatibility. Certain properties cannot be jointly defined for the same system at the same time. The incompatibility is expressed quantitatively by Heisenberg's uncertainty principle. For example, if a particle at a particular instant has a definite location, it is meaningless to speak of its momentum at that instant.

3. During an observation, the system must interact with a laboratory device. When that device makes a measurement, the wave function of the systems is said to collapse, or irreversibly reduce to an eigenstate of the observable that is registered.[12]

4. The results provided by measuring devices are essentially classical, and should be described in ordinary language. This was particularly emphasized by Bohr, and was accepted by Heisenberg.[13]

5. The description given by the wave function is probabilistic. This principle is called the Born rule, after Max Born.

6. The wave function expresses a necessary and fundamental wave–particle duality. This should be reflected in ordinary language accounts of experiments. An experiment can show particle-like properties, or wave-like properties, according to the complementarity principle of Niels Bohr.[14]

7. The inner workings of atomic and subatomic processes are necessarily and essentially inaccessible to direct observation, because the act of observing them would greatly affect them.

8. When quantum numbers are large, they refer to properties which closely match those of the classical description. This is the correspondence principle of Bohr and Heisenberg.

5 Metaphysics of the wave function

The Copenhagen Interpretation denies that the wave function provides a directly apprehensible image of an ordinary material body or a discernible component of some such,[15][16] or anything more than a theoretical concept.

In metaphysical terms, the Copenhagen interpretation views quantum mechanics as providing knowledge of phenomena, but not as pointing to 'really existing objects', which it regarded as otiose residues of ordinary intuition. This makes it an epistemic theory. This may be contrasted with Einstein's view, that physics should look for 'really existing objects', making itself an ontic theory. [17]

The metaphysical question is sometimes asked: "Could quantum mechanics be extended by adding so-called "hidden variables" to the mathematical formalism, to convert it from an epistemic to an ontic theory?" The Copenhagen interpretation answers this with a strong 'No'.[18] It is sometimes alleged, for example by J.S. Bell, that Einstein opposed the Copenhagen interpretation because he believed that the answer to that question of "hidden variables" was 'Yes'. That allegation has achieved mythical potency, but is mistaken. Countering that myth, Max Jammer writes "Einstein never proposed a hidden variable theory."[19] Einstein explored the possibility of a hidden variable theory, and wrote a paper describing his exploration, but withdrew it from publication because he felt it was faulty.[20][21]

Because it asserts that a wave function becomes 'real' only when the system is observed, the term "subjective" is sometimes proposed for the Copenhagen interpretation. This term is rejected by many Copenhagenists because the process of observation is mechanical and does not depend on the individuality of the observer.

Some authors have proposed that Bohr was influenced by positivism (or even pragmatism). On the other hand, Bohr and Heisenberg were not in complete agreement, and they held different views at different times. Heisenberg in particular was prompted to move towards realism.[22]

Even if the wave function is not regarded as real, there is still a divide between those who treat it as definitely and entirely subjective, and those who are noncommittal or agnostic about the subject. An example of the agnostic view is given by Carl Friedrich von Weizsäcker, who, while participating in a colloquium at Cambridge, denied that the Copenhagen interpretation asserted “What cannot be observed does not exist.” He suggested instead that the Copenhagen interpretation follows the principle “What is observed certainly exists; about what is not observed we are still free to make suitable assumptions. We use that freedom to avoid paradoxes.”[8]

6 Born rule

Max Born speaks of his probability interpretation as a “statistical interpretation” of the wave function,[23][24] and the Born rule is essential to the Copenhagen interpretation.[25] But writers do not all follow the same terminology.

The phrase 'statistical interpretation', referring to the 'ensemble interpretation', often indicates an interpretation of the Born rule somewhat different from the Copenhagen interpretation.[26][27] For the Copenhagen interpretation, it is axiomatic that the wave function exhausts all that can ever be known in advance about a particular occurrence of the system. The 'statistical' or 'ensemble' interpretation, on the other hand, is explicitly agnostic about whether the information in the wave function is exhaustive of what might be known in advance. It sees itself as more 'minimal' than the Copenhagen interpretation in its claims. It only goes as far as saying that on every occasion of observation, some actual value of some property is found, and that such values are found probabilistically, as detected by many occasions of observation of the same system. The many occurrences of the system are said to constitute an 'ensemble', and they jointly reveal the probability through these occasions of observation. Though they all have the same wave function, the elements of the ensemble might not be identical to one another in all respects, according to the 'agnostic' interpretations. They may, for all we know, beyond current knowledge and beyond the wave function, have individual distinguishing properties. For present-day science, the experimental significance of these various forms of Born’s rule is the same, since they make the same predictions about the probability distribution of outcomes of observations, and the unobserved or unactualized potential properties are not accessible to experiment.

7 Nature of collapse

Main articles: wave function collapse and quantum decoherence

Those who hold to the Copenhagen interpretation are willing to say that a wave function involves the various probabilities that a given event will proceed to certain different outcomes. But when the apparatus registers one of those outcomes, no probabilities or superposition of the others linger.[28]

According to Howard, wave function collapse is not mentioned in the writings of Bohr.[3]

Some argue that the concept of the collapse of a “real” wave function was introduced by Heisenberg and later developed by John von Neumann in 1932.[29] However, Heisenberg spoke of the wavefunction as representing available knowledge of a system, and did not use the term “collapse” per se, but instead termed it “reduction” of the wavefunction to a new state representing the change in available knowledge which occurs once a particular phenomenon is registered by the apparatus (often called “measurement”).[30]

In 1952 David Bohm developed decoherence, an *explanatory mechanism* for the *appearance* of wave function collapse. Bohm applied decoherence to Louis DeBroglie's pilot wave theory, producing Bohmian mechanics,[31][32] the first successful hidden variables interpretation of quantum mechanics. Decoherence was then used by Hugh Everett in 1957 to form the core of his many-worlds interpretation.[33] However decoherence was largely[34] ignored until the 1980s.[35][36]

8 Non-separability of the wave function

The domain of the wave function is configuration space, an abstract object quite different from ordinary physical space–time. At a single “point” of configuration space, the wave function collects probabilistic information about several distinct particles, that respectively have physically space-like separation. So the wave function is said to supply a non-separable representation. This reflects a feature of the quantum world that was recognized by Einstein as early as 1905.

In 1927, Bohr drew attention to a consequence of non-separability. The evolution of the system, as determined by the Schrödinger equation, does not display particle trajectories through space–time. It is possible to extract trajectory information from such evolution, but not simultaneously to extract energy–momentum information. This incompatibility is expressed in the Heisenberg uncertainty principle. The two kinds of information have to be extracted on different occasions, because of the non-separability of the wave function representation. In Bohr's thinking, space–time visualizability meant trajectory information. Again, in Bohr's thinking, 'causality' referred to energy–momentum transfer; in his view, lack of energy–momentum knowledge meant lack of 'causality' knowledge. Therefore Bohr thought that knowledge respectively of 'causality' and of space–time visualizability were incompatible but complementary.[3]

9 Wave–particle dilemma

Further information: Wave-particle duality

The term 'Copenhagen interpretation' was, it seems, invented by Heisenberg in 1955. It is often assumed that the 'Copenhagen interpretation' was agreed between Bohr and Heisenberg, with perhaps Born included. The term Copenhagen interpretation, however, is not well defined when one asks about the wave–particle dilemma, because Bohr and Heisenberg had different or perhaps disagreeing views on it.

According to Camilleri, Bohr thought that the distinction between a wave view and a particle view was defined by a distinction between experimental setups, while, differing, Heisenberg thought that it was defined by the possibility of viewing the mathematical formulas as referring to waves or particles. Bohr thought that a particular experimental setup would display either a wave picture or a particle picture, but not both. Heisenberg thought that every mathematical formulation was capable of both wave and particle interpretations.[37][38] Looking at it slightly differently, Heisenberg's view was about quantum field theory. Thus one is left in a dilemma to know whether the 'Copenhagen interpretation' is the one of Bohr (one or the other) or the one of Heisenberg (always both).

Alfred Landé was for a long time considered orthodox. He did, however, take the Heisenberg viewpoint, in so far as he thought that the wave function was always mathematically open to both interpretations. Eventually this led to his being considered unorthodox, partly because he did not accept Bohr's one-or-the-other view, preferring Heisenberg's always-both view. Another part of the reason for branding Landé unorthodox was that he recited, as did Heisenberg, the 1923 work[39] of old-quantum-theorist William Duane, which anticipated a quantum mechanical theorem that had not been recognized by Born. That theorem seems to make the always-both view, like the one adopted by Heisenberg, rather cogent. One might say "It's there in the mathematics", but that is not a physical statement that would have convinced Bohr. Perhaps the main reason for attacking Landé is that his work demystified the phenomenon of diffraction of particles of matter, such as buckyballs.[40]

10 Acceptance among physicists

Throughout much of the twentieth century the Copenhagen interpretation had overwhelming acceptance among physicists. Although astrophysicist and science writer John Gribbin described it as having fallen from primacy after the 1980s,[41] according to a poll conducted at a quantum mechanics conference in 1997,[42] the Copenhagen interpretation remained the most widely accepted specific interpretation of quantum mechanics among physicists. In more recent polls conducted at various quantum mechanics conferences, varying results have been found.[43][44][45] Often, as is the case with the 4 referenced sources, the acceptance of the Copenhagen interpretation as the preferred view of the underlying nature was below 50% amongst the surveyed.

11 Consequences

The nature of the Copenhagen Interpretation is exposed by considering a number of experiments and paradoxes.

1. Schrödinger's cat

   This thought experiment highlights the implications that accepting uncertainty at the microscopic level has on macroscopic objects. A cat is put in a sealed box, with its life or death made dependent on the state of a subatomic particle. Thus a description of the cat during the course of the experiment—having been entangled with the state of a subatomic particle—becomes a "blur" of "living and dead cat." But this can't be accurate because it implies the cat is actually both dead and alive until the box is opened to check on it. But the cat, if it survives, will only remember being alive. Schrödinger resists "so naively accepting as valid a 'blurred model' for representing reality."[46] *How can the cat be both alive and dead?*

   The Copenhagen Interpretation: The wave function reflects our knowledge of the system. The wave function $(|\text{dead}\rangle + |\text{alive}\rangle)/\sqrt{2}$ means that, once the cat is observed, there is a 50% chance it will be dead, and 50% chance it will be alive.

2. Wigner's Friend

   Wigner puts his friend in with the cat. The external observer believes the system is in the state $(|\text{dead}\rangle + |\text{alive}\rangle)/\sqrt{2}$. His friend, however, is convinced that the cat is alive, i.e. for him, the cat is in the state $|\text{alive}\rangle$. *How can Wigner and his friend see different wave functions?*

The Copenhagen Interpretation: The answer depends on the positioning of Heisenberg cut, which can be placed arbitrarily. If Wigner's friend is positioned on the same side of the cut as the external observer, his measurements collapse the wave function for both observers. If he is positioned on the cat's side, his interaction with the cat is not considered a measurement.

3. Double-slit diffraction

Light passes through double slits and onto a screen resulting in a diffraction pattern. *Is light a particle or a wave?*

The Copenhagen Interpretation: Light is neither. A particular experiment can demonstrate particle (photon) or wave properties, but not both at the same time (Bohr's Complementarity Principle).

The same experiment can in theory be performed with *any* physical system: electrons, protons, atoms, molecules, viruses, bacteria, cats, humans, elephants, planets, etc. In practice it has been performed for light, electrons, buckminsterfullerene,[47][48] and some atoms. Due to the smallness of Planck's constant it is practically impossible to realize experiments that directly reveal the wave nature of any system bigger than a few atoms but, in general, quantum mechanics considers all matter as possessing both particle and wave behaviors. The greater systems (like viruses, bacteria, cats, etc.) are considered as "classical" ones but only as an approximation, not exact.

4. EPR (Einstein–Podolsky–Rosen) paradox

Entangled "particles" are emitted in a single event. Conservation laws ensure that the measured spin of one particle must be the opposite of the measured spin of the other, so that if the spin of one particle is measured, the spin of the other particle is now instantaneously known. The most discomforting aspect of this paradox is that the effect is instantaneous so that something that happens in one galaxy could cause an instantaneous change in another galaxy. But, according to Einstein's theory of special relativity, no information-bearing signal or entity can travel at or faster than the speed of light, which is finite. Thus, it seems as if the Copenhagen interpretation is inconsistent with special relativity.

The Copenhagen Interpretation: Assuming wave functions are not real, wave-function collapse is interpreted subjectively. The moment one observer measures the spin of one particle, he knows the spin of the other. However, another observer cannot benefit until the results of that measurement have been relayed to him, at less than or equal to the speed of light.

Copenhagenists claim that interpretations of quantum mechanics where the wave function is regarded as real have problems with EPR-type effects, since they imply that the laws of physics allow for influences to propagate at speeds greater than the speed of light. However, proponents of many worlds[49] and the transactional interpretation[50][51] (TI) maintain that Copenhagen interpretation is fatally non-local.

The claim that EPR effects violate the principle that information cannot travel faster than the speed of light have been countered by noting that they cannot be used for signaling because neither observer can control, or predetermine, what he observes, and therefore cannot manipulate what the other observer measures. However, this is a somewhat spurious argument, in that the speed of light limitation applies to all information, not to what can or cannot be subsequently done with the information. On the other hand, the special theory of relativity contains no notion of information at all. The fact that no classical body can exceed the speed of light (no matter how much acceleration is applied) is a consequence of classical relativistic mechanics. As the correlation between the two particles in an EPR experiment is most probably not established by classical bodies or light signals, the displayed non-locality is not at odds with special relativity.

A further argument against Copenhagen interpretation is that relativistic difficulties about establishing which measurement occurred first or last, or whether they occurred quite at the same time, also undermine the idea that in "different" instants and measurements different outcomes can occur. The spin would be kept as a "constant" for a continuous interval of time, i.e. as a real *variable*, and thus it would seem to violate the general rule (of the classic Copenhagen interpretation) that every measurement gives nothing else than a random outcome subject to certain probabilities.

12 Criticism

The completeness of quantum mechanics (thesis 1) was attacked by the Einstein–Podolsky–Rosen thought experiment which was intended to show that quantum mechanics could not be a complete theory.

Experimental tests of Bell's inequality using particles have supported the quantum mechanical prediction of entanglement.

The Copenhagen Interpretation gives special status to measurement processes without clearly defining them or explaining their peculiar effects. In his article entitled "Criticism and Counterproposals to the Copenhagen Interpretation of Quantum Theory," countering the view of Alexandrov that (in Heisenberg's paraphrase) "the wave function in configuration space characterizes the objective state of the electron." Heisenberg says,

> Of course the introduction of the observer must not be misunderstood to imply that some kind of subjective features are to be brought into the description of nature. The observer has, rather, only the function of registering decisions, i.e., processes in space and time, and it does not matter whether the observer is an apparatus or a human being; but the registration, i.e., the transition from the "possible" to the "actual," is absolutely necessary here and cannot be omitted from the interpretation of quantum theory.[52]

Many physicists and philosophers have objected to the Copenhagen interpretation, both on the grounds that it is non-deterministic and that it includes an undefined measurement process that converts probability functions into non-probabilistic measurements. Einstein's comments "I, at any rate, am convinced that He (God) does not throw dice."[53] and "Do you really think the moon isn't there if you aren't looking at it?"[54] exemplify this. Bohr, in response, said, "Einstein, don't tell God what to do."[55]

Steven Weinberg in "Einstein's Mistakes", *Physics Today*, November 2005, page 31, said:

> All this familiar story is true, but it leaves out an irony. Bohr's version of quantum mechanics was deeply flawed, but not for the reason Einstein thought. The Copenhagen interpretation describes what happens when an observer makes a measurement, but the observer and the act of measurement are themselves treated classically. This is surely wrong: Physicists and their apparatus must be governed by the same quantum mechanical rules that govern everything else in the universe. But these rules are expressed in terms of a wave function (or, more precisely, a state vector) that evolves in a perfectly deterministic way. So where do the probabilistic rules of the Copenhagen interpretation come from?
>
> Considerable progress has been made in recent years toward the resolution of the problem, which I cannot go into here. It is enough to say that neither Bohr nor Einstein had focused on the real problem with quantum mechanics. The Copenhagen rules clearly work, so they have to be accepted. But this leaves the task of explaining them by applying the deterministic equation for the evolution of the wave function, the Schrödinger equation, to observers and their apparatus.

The problem of thinking in terms of classical measurements of a quantum system becomes particularly acute in the field of quantum cosmology, where the quantum system is the universe.[56]

E. T. Jaynes,[57] from a Bayesian point of view, argued that probability is a measure of a state of information about the physical world. Quantum mechanics under the Copenhagen Interpretation interpreted probability as a physical phenomenon, which is what Jaynes called a Mind Projection Fallacy.

Common criticisms of the Copenhagen interpretation often lead to the problem of continuum of random occurrences: whether in time (as subsequent measurements, which under certain interpretations of the measurement problem may happen continuously) or even in space. A recent experiment showed that a particle may leave a trace about the path which it used when travelling as a wave – and that this trace exhibits equality of both paths.[58] If such result is raised to the rank of a wave-only non-transactional worldview and proved better – i.e. that a particle is in fact a continuum of points capable of acting independently but under a common wavefunction – it would rather support theories such as Bohm's one (with its guiding towards the centre of orbital and spreading of physical properties over it) than interpretations which presuppose full randomness, because with the latter it will be problematic to demonstrate universally and in all practical cases how can a particle remain coherent in time, in spite of non-zero probabilities of its individual points going into regions distant from the centre of mass (through a continuum of different random determinations).[59] An alternative possibility would be to assume that there is a finite number of instants/points within a given time or area, but theories which try to quantize the space or time itself seem to be fatally incompatible with the special relativity.

The view that particle diffraction logically guarantees the need for a wave interpretation has been questioned. A recent experiment has carried out the two-slit protocol with helium atoms.[60] The basic physics of quantal momentum transfer considered here was originally pointed out in 1923, by William Duane, before quantum mechanics was invented.[39] It was later recognized by Heisenberg[61] and by Pauling.[62] It was championed against orthodox ridicule by Alfred Landé.[63] It has also recently been considered by Van Vliet.[64][65] If the diffracting slits are considered as classical objects, theoretically ideally seamless, then a wave interpretation seems necessary, but if the diffracting slits are considered physically, as quantal objects exhibiting collective quantal motions, then the particle-only and wave-only interpretations seem perhaps equally valid.

13 Alternatives

Further information: Interpretations of quantum mechanics

The Ensemble interpretation is similar; it offers an interpretation of the wave function, but not for single particles. The consistent histories interpretation advertises itself as "Copenhagen done right". Although the Copenhagen interpretation is often confused with the idea that consciousness causes collapse, it defines an "observer" merely as that which collapses the wave function.[52] Quantum information theories are more recent, and have attracted growing support.[66][67]

Under realism and indeterminism, if the wave function is regarded as ontologically real, and collapse is entirely rejected, a many worlds theory results. If wave function collapse is regarded as ontologically real as well, an objective collapse theory is obtained. Under realism and determinism (as well as non-localism), a hidden variable theory exists, e.g., the de Broglie–Bohm interpretation, which treats the wavefunction as real, position and momentum as definite and resulting from the expected values, and physical properties as spread in space. For an atemporal indeterministic interpretation that "makes no attempt to give a 'local' account on the level of determinate particles",[68] the conjugate wavefunction, ("advanced" or time-reversed) of the relativistic version of the wavefunction, and the so-called "retarded" or time-forward version[69] are both regarded as real and the transactional interpretation results.[68]

Many physicists have subscribed to the instrumentalist interpretation of quantum mechanics, a position often equated with eschewing all interpretation. It is summarized by the sentence "Shut up and calculate!". While this slogan is sometimes attributed to Paul Dirac[70] or Richard Feynman, it seems to be due to David Mermin.[71]

14 See also

- Bohr–Einstein debates
- Fifth Solvay Conference
- Interpretations of quantum mechanics
- Philosophical interpretation of classical physics
- Physical ontology
- Popper's experiment
- De Broglie–Bohm theory

15 Notes and references

[1] Hermann Wimmel (1992). *Quantum physics & observed reality: a critical interpretation of quantum mechanics*. World Scientific. p. 2. ISBN 978-981-02-1010-6. Retrieved 9 May 2011.

[2] J. Mehra and H. Rechenberg, *The historical development of quantum theory*, Springer-Verlag, 2001, p. 271.

[3] Howard, Don (2004). "Who invented the Copenhagen Interpretation? A study in mythology". *Philosophy of Science* **71** (5): 669–682. doi:10.1086/425941. JSTOR 10.1086/425941.

[4] Bohm, David (1952). "A Suggested Interpretation of the Quantum Theory in Terms of "Hidden" Variables. I & II". *Physical Review* **85** (2): 166–193. Bibcode:1952PhRv...85..166B. doi:10.1103/PhysRev.85.166.

[5] H. Kragh, *Quantum generations: A History of Physics in the Twentieth Century*, Princeton University Press, 1999, p. 210. ("the term 'Copenhagen interpretation' was not used in the 1930s but first entered the physicist's vocabulary in 1955 when Heisenberg used it in criticizing certain unorthodox interpretations of quantum mechanics.")

[6] Werner Heisenberg, *Physics and Philosophy*, Harper, 1958

[7] Olival Freire Jr., "Science and exile: David Bohm, the hot times of the Cold War, and his struggle for a new interpretation of quantum mechanics", *Historical Studies on the Physical and Biological Sciences*, Volume 36, Number 1, 2005, pp. 31–35. ("I avow that the term 'Copenhagen interpretation' is not happy since it could suggest that there are other interpretations, like Bohm assumes. We agree, of course, that the other interpretations are nonsense, and I believe that this is clear in my book, and in previous papers. Anyway, I cannot now, unfortunately, change the book since the printing began enough time ago.")

[8] Cramer, John G. (July 1986). "The Transactional Interpretation of Quantum Mechanics". *Reviews of Modern Physics* **58** (3): 649. Bibcode:1986RvMP...58..647C. doi:10.1103/revmodphys.58.647.

[9] In fact Bohr and Heisenberg never totally agreed on how to understand the mathematical formalism of quantum mechanics. Bohr once distanced himself from what he considered to be Heisenberg's more subjective interpretation Stanford Encyclopedia of Philosophy

[10] "There seems to be at least as many different Copenhagen interpretations as people who use that term, probably there are more. For example, in two classic articles on the foundations of quantum mechanics, Ballentine (1970) and Stapp (1972) give diametrically opposite definitions of 'Copenhagen.'", Asher Peres (2002). "Popper's experiment and the Copenhagen interpretation". *Stud. History*

Philos. Modern Physics **33** (23): 10078. arXiv:quant-ph/9910078. Bibcode:1999quant.ph.10078P.

[11] "... for the ″hidden parameters″ of Bohm's interpretation are of such a kind that they can *never* occur in the description of real processes, if the quantum theory remains unchanged." Heisenberg, W. (1955). The development of the quantum theory, pp. 12–29 in *Niels Bohr and the Development of Physics*, ed. W. Pauli with the assistance of L. Rosenfeld and V. Weisskopf, Pergamon, London, at p. 18.

[12] "It is well known that the 'reduction of the wave packets' always appears in the Copenhagen interpretation when the transition is completed from the possible to the actual. The probability function, which covered a wide range of possibilities, is suddenly reduced to a much narrower range by the fact that the experiment has led to a definite result, that actually a certain event has happened. In the formalism this reduction requires that the so-called interference of probabilities, which is the most characteristic phenomena [*sic*] of quantum theory, is destroyed by the partly undefinable and irreversible interactions of the system with the measuring apparatus and the rest of the world." Heisenberg, W. (1959/1971). Criticism and counterproposals to the Copenhagen interpretation of quantum theory, Chapter 8, pp. 114–128, in *Physics and Philosophy: the Revolution in Modern Science*, third impression 1971, George Allen & Unwin, London, at p. 125.

[13] "Every description of phenomena, of experiments and their results, rests upon language as the only means of communication. The words of this language represent the concepts of ordinary life, which in the scientific language of physics may be refined to the concepts of classical physics. These concepts are the only tools for an unambiguous communication about events, about the setting up of experiments and about their results." Heisenberg, W. (1959/1971). Criticism and counterproposals to the Copenhagen interpretation of quantum theory, Chapter 8, pp. 114–128, in *Physics and Philosophy: the Revolution in Modern Science*, third impression 1971, George Allen & Unwin, London, at p. 127.

[14] "... there is no reason to consider these matter waves as less real than particles." Heisenberg, W. (1959/1971). Criticism and counterproposals to the Copenhagen interpretation of quantum theory, Chapter 8, pp. 114–128, in *Physics and Philosophy: the Revolution in Modern Science*, third impression 1971, George Allen & Unwin, London, at p. 118.

[15] Bohr, N. (1928). 'The quantum postulate and the recent development of atomic theory', *Nature*, **121**: 580–590, doi :10.1038/121580a0, p. 586: "there can be no question of an immediate connexion with our ordinary conceptions".

[16] Heisenberg, W. (1959/1971). 'Language and reality in modern physics', Chapter 10, pp. 145–160, in *Physics and Philosophy: the Revolution in Modern Science*, George Allen & Unwin, London, ISBN 0-04-530016 X, p. 153: "our common concepts cannot be applied to the structure of the atoms."

[17] Jammer, M. (1982). 'Einstein and quantum physics', pp. 59–76 in *Albert Einstein: Historical and Cultural Perspectives; the Centennial Symposium in Jerusalem*, edited by G. Holton, Y. Elkana, Princeton University Press, Princeton NJ, ISBN 0-691-08299-5. On pp. 73–74, Jammer quotes a 1952 letter from Einstein to Besso: "The present quantum theory is unable to provide the description of a real state of physical facts, but only of an (incomplete) knowledge of such. Moreover, the very concept of a real factual state is debarred by the orthodox theoreticians. The situation arrived at corresponds almost exactly to that of the good old Bishop Berkeley."

[18] Heisenberg, W. (1927). Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik, *Z. Phys.* **43**: 172–198. Translation as 'The actual content of quantum theoretical kinematics and mechanics' here: "Since the statistical nature of quantum theory is so closely [linked] to the uncertainty in all observations or perceptions, one could be tempted to conclude that behind the observed, statistical world a "real" world is hidden, in which the law of causality is applicable. We want to state explicitly that we believe such speculations to be both fruitless and pointless. The only task of physics is to describe the relation between observations."

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[22] "Historically, Heisenberg wanted to base quantum theory solely on observable quantities such as the intensity of spectral lines, getting rid of all intuitive (anschauliche) concepts such as particle trajectories in space–time. This attitude changed drastically with his paper in which he introduced the uncertainty relations – there he put forward the point of view that it is the theory which decides what can be observed. His move from positivism to operationalism can be clearly understood as a reaction on the advent of Schrödinger's wave mechanics which, in particular due to its intuitiveness, became soon very popular among physicists. In fact, the word anschaulich (intuitive) is contained in the title of Heisenberg's paper.", from Claus Kiefer (2002). "On the interpretation of quantum theory – from Copenhagen to the present day". arXiv:quant-ph/0210152.

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way by von Neumann, ..." Born, M. (1953). The interpretation of quantum mechanics, *Brit. J. Phil. Sci.*, **4**(14): 95–106.

[25] Bohr, N. (1928). 'The quantum postulate and the recent development of atomic theory', *Nature*, **121**: 580–590, doi :10.1038/121580a0, p. 586: "In this connexion [Born] succeeded in obtaining a statistical interpretation of the wave functions, allowing a calculation of the probability of the individual transition processes required by the quantum postulate.".

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[27] Born, M. (1949). Einstein's statistical theories, in *Albert Einstein: Philosopher Scientist*, ed. P.A. Schilpp, Open Court, La Salle IL, volume 1, pp. 161–177.

[28] "Of course the introduction of the observer must not be misunderstood to imply that some kind of subjective features are to be brought into the description of nature." Heisenberg, W. (1959/1971). Criticism and counterproposals to the Copenhagen interpretation of quantum theory, Chapter 8, pp. 114–128, in *Physics and Philosophy: the Revolution in Modern Science*, third impression 1971, George Allen & Unwin, London, at p. 121.

[29] "the "collapse" or "reduction" of the wave function. This was introduced by Heisenberg in his uncertainty paper [3] and later postulated by von Neumann as a dynamical process independent of the Schrodinger equation", Claus Kiefer (2002). "On the interpretation of quantum theory – from Copenhagen to the present day". arXiv:quant-ph/0210152.

[30] W. Heisenberg "Über den anschaulichen Inhalt der quantentheoretischen Kinematik und Mechanik," *Zeitschrift für Physik*, Volume 43, 172–198 (1927), as translated by John Wheeler and Wojciech Zurek, in *Quantum Theory and Measurement* (1983), p. 74. ("[The] determination of the position selects a definite "q" from the totality of possibilities and limits the options for all subsequent measurements. ... [T]he results of later measurements can only be calculated when one again ascribes to the electron a "smaller" wavepacket of extension λ (wavelength of the light used in the observation). Thus, every position determination reduces the wavepacket back to its original extension λ.")

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[32] David Bohm, A Suggested Interpretation of the Quantum Theory in Terms of "Hidden Variables", II, *Physical Review*, (1952), 85, pp 180–193

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[50] Relativity and Causality in the Transactional Interpretation

[51] Collapse and Nonlocality in the Transactional Interpretation

[52] Werner Heisenberg, *Physics and Philosophy*, Harper, 1958, p. 137.

[53] “God does not throw dice” quote

[54] A. Pais, *Einstein and the quantum theory*, Reviews of Modern Physics **51**, 863–914 (1979), p. 907.

[55] Bohr recollected his reply to Einstein at the 1927 Solvay Congress in his essay “Discussion with Einstein on Epistemological Problems in Atomic Physics”, in *Albert Einstein, Philosopher–Scientist*, ed. Paul Arthur Shilpp, Harper, 1949, p. 211: "...in spite of all divergencies of approach and opinion, a most humorous spirit animated the discussions. On his side, Einstein mockingly asked us whether we could really believe that the providential authorities took recourse to dice-playing ("*ob der liebe Gott würfelt*"), to which I replied by pointing at the great caution, already called for by ancient thinkers, in ascribing attributes to Providence in everyday language.” Werner Heisenberg, who also attended the congress, recalled the exchange in *Encounters with Einstein*, Princeton University Press, 1983, p. 117,: “But he [Einstein] still stood by his watchword, which he clothed in the words: 'God does not play at dice.' To which Bohr could only answer: 'But still, it cannot be for us to tell God, how he is to run the world.'"

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16 Further reading

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17 External links

- Copenhagen Interpretation (*Stanford Encyclopedia of Philosophy*)
- Physics FAQ section about Bell's inequality
- The Copenhagen Interpretation of Quantum Mechanics
- Preprint of Afshar Experiment

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